CALIFORNIA
ENERGY
COMMISSION

Public Interest Energy Research Program
Research Devlopment and Demonstration Plan

Attachment I - Modeling Regional Climate Change in California

Contractor/Consultant Report

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Executive Summary

This roadmap addresses the issue of regional climate modeling, with the purpose of identifying those research issues that need to be addressed if California is to respond in an adequate and timely manner to future climate change. Climate changes in California, especially in the winter precipitation, may have serious impacts on the state's water and energy supply, while changes in coastal and regional climates may affect the state's economy and resources in significant ways.

There is presently considerable uncertainty surrounding the possible future climate changes in California, and research needs to focus on the quantification and reduction of these uncertainties. It is expected that improved high-resolution regional models will be able to portray the magnitude and distribution of future climate changes in California with significantly more certainty than now available, including (but not limited to) the expected changes in temperature and precipitation. To this end, PIER should support a balanced research program in which projects focus on the evaluation and intercomparison of regional climate models for California, the development of improved statistical downscaling techniques for hydrologic applications, and the assembly of a regional California climate databank.

In the short-term (1–3 years) this roadmap recommends addressing the objectives summarized in the table below:

Objective	**Projected Cost ($000 per year)**
Design a model intercomparison protocol	800* (for both)
Perform control simulations and analyze results	
Evaluate downscaling methods	400* (for both)
Analyze errors of hydrologic applications	
Develop a California climate database	600* (for both)
Develop a data access system	
Total Short-term Cost per Year	**1,800**

Note: An asterisk (*) indicates a high probability that approximately equal funding will be available for each project from other sources. The figure given is the California Energy Commission's projected per-year expenditure over the short-term period.

The Public Interest Energy Research (PIER) Climate Change Research Plan also identifies mid-term (3–10 year) and long-term (10–20 year) goals, all of which build on the short-term work listed above. This roadmap outlines a comprehensive research agenda that would be necessary to fully address the research gaps identified in this document. PIER, however, due to the limited funding, will be able to support only some of the identified areas of research. PIER is currently examining all of the roadmaps to determine which projects should be supported with PIER funding.

Roadmap Organization

This roadmap is intended to communicate to an audience that is technically acquainted with the issue. The sections build upon each other to provide a framework and justification for the proposed research and development.

Section 1 states the issue to be addressed. *Section 2: Public Interest Vision* provides an overview of research needs in this area and how PIER plans to address those needs. *Section 3: Background* establishes the context of PIER's climate change work in the area of modeling regional climate change. *Section 4: Current Research and Research Needs* surveys current projects and identifies specific research needs that are not already being addressed by those projects. *Section 5: Goals* outlines proposed PIEREA activities that will meet those needs. *Section 6: Leveraging R&D Investments* identifies methods and opportunities to help ensure that the investment of research funds will achieve the greatest public benefits. *Section 7: Areas Not Addressed by this Roadmap* identifies areas related to climate change research in this area that the proposed activities do not address. *Appendix A: Current Status of Programs* offers an overview of work being done to address issues of modeling regional climate change.

Acronyms

ACACIA	A Consortium for the Application of Climate Impact Assessments
ACPI	Accelerated Climate Prediction Initiative
ARB	California Air Resources Board
CDEC	California Data Exchange Center
CCPP	Climate Change Prediction Program
DOE	U.S. Department of Energy
DRI	Western Regional Climate Center at the Desert Research Institute (University of Nevada)
ENSO	El Niño–Southern Oscillation
EPRI	Electric Power Research Institute
GCM	global general circulation model
IPCC	Intergovernmental Panel on Climate Change
LBNL	Lawrence Berkeley National Laboratory
LLNL	Lawrence Livermore National Laboratory
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
PCMDI	Program for Climate Model Diagnosis and Intercomparison
PIEREA	Public Interest Energy Research, Environmental Area (California Energy Commission)
PNNL	Pacific Northwest National Laboratory
PIRCS	Program to Intercompare Regional Climate Simulations
RCM	Regional climate model
SIO	Scripps Institution of Oceanography
USGS	U.S. Geological Survey
USGCRP	U.S. Global Change Research Program

1. Issue Statement

It is necessary to develop more accurate regional climate models that will provide physically realistic estimates of potential changes in key variables as part of California's climate change impact assessment process. It is also necessary to design and implement a coordinated regional climate modeling program for the State.

2. Public Interest Vision

Regional climate modeling attempts to provide a more detailed spatial depiction of possible future climate changes than that provided by the conventional global models. From the information provided by regional models, other models (either dynamical or statistical) may in turn address local or site-specific variables such as snow accumulation or river runoff as part of the climate change impact assessment process. Regional models thus bridge the gap between the large scale and the local scale on which most impacts of climate change actually occur. The need for such information is especially strong in California, where complex mountain ranges and an extended coastline support a variety of regional and local climates. There is also need for improved information on the occurrence of extreme events, such as floods, persistent El Niño conditions, and extended hot spells. The consequences of climate change may be particularly serious in California, in view of the threats to the state's water supply and power infrastructure (Gleick 1987). The design and implementation of a coordinated regional climate modeling program for California is therefore an important challenge.

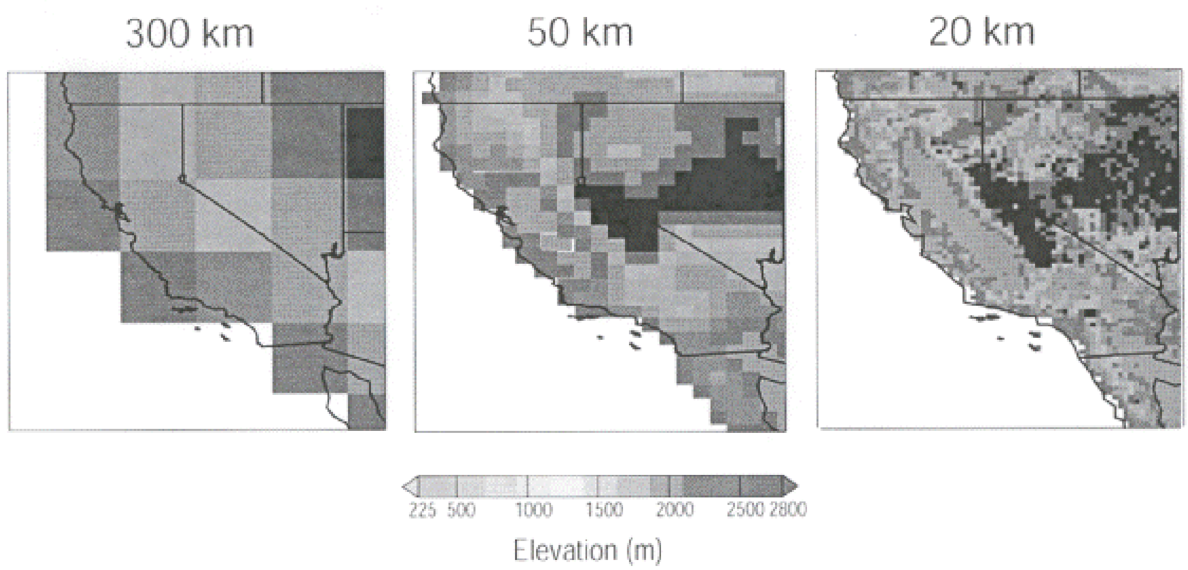
Implementation of this roadmap will reduce the uncertainties in the projection of future regional climate changes in California, and will thereby provide guidelines for the more effective management of the state's water and energy resources in the face of the expected increases in population and development. Completion of the recommended research program will significantly advance our knowledge of the expected regional climate changes throughout California, and will serve as a model for similar studies in other states and regions.

3. Background

3.1 State of the Science

Regional climate modeling—defined as the application of dynamical models over a region of the Earth (of the order of 1000 km) with horizontal resolutions of the order of 10–100 km—was first performed about ten years ago (Giorgi 1990; Dickinson et al. 1989). The technique used was to imbed a regional climate model (RCM) within a global general circulation model (GCM), with the latter providing the lateral boundary conditions required by the regional model. During the ensuing years, this approach has been used in many simulations of regional climate and climate change with a variety of RCMs and GCMs, as recently summarized by Giorgi and Mearns (1999), the Intergovernmental Panel on Climate Change (IPCC) (Giorgi and Hewitson 2001), and Pan et al. (2001). Although there are a number of outstanding technical issues with regional climate models (such as the their lateral boundary conditions, their resolution and location, and their compatibility with the driving GCM), it is generally recognized that RCMs are able to provide a useful portrayal of climate and climate change on scales smaller than those seen in a GCM, especially in regions of varied topography such as California.

The importance of resolving regional topography is illustrated in Figure 1. The higher-resolution results from the limited number of RCMs that have been applied to California in climate change simulations generally show higher temperatures and precipitation in the Sierra than do the direct results from GCMs (Snyder et al. 2001; National Research Council 2001; and Tom Wigley, personal comm.), and offer the opportunity for further improvement by statistical downscaling to specific sites.



The orography of California as resolved by various grid-box sizes. The resolution of most GCMs (~300km) gives no detail of California's orography. At the 50km resolution common to many regional models, the Central Valley and Sierra begin to be discernible , while a grid size of 20 km reveals their regional structure as well as that of the Coast Ranges.

Figure 1. Orographic[1] Representation of California from Models at Different Resolutions

In spite of this increase in precision, regional climate models continue to be subject to the shortcomings of the driving GCM. These GCM errors (which vary considerably from model to model) often take the form of a cold bias in the higher latitudes, the underestimation of variability, and the deficient portrayal of the effects of clouds and surface processes. Recent efforts to improve RCMs have focused on reduction of the errors

[1] Orography is the branch of physical geography associated with mountains.

introduced by the imposed lateral boundary conditions[2] (Noguer et al. 1998; Qian et al. 1999) and improvement of the RCMs' parameterizations[3] (Giorgi and Shields 1999). Advances in the development of GCM that are expected over the next several years include the use of higher resolution, and the incorporation of: a coupled carbon cycle (for both terrestrial and oceanic components), interactive vegetation, and improved aerosol/cloud physics. Regional climate model development should keep pace with these advances to the extent possible.

The need for climate information at high spatial resolution may also be pursued by statistically relating the output of GCM simulations to the climate (or climate-related processes) at specific locations. Such *statistical downscaling* attempts to correct the biases of the GCM by correlating the variability of selected model variables with those observed on a smaller scale, and assumes that this relation will apply to future climate as well. This technique has been widely applied in recent years, and Wilby and Wigley (1997) have recently summarized the methods used. Depending upon the application, such statistical downscaling can achieve a level of skill comparable to that provided by regional climate models (Mearns et al. 1999; Leung 2002). Although it has the advantages of simplicity and economy, statistical downscaling is generally unable to provide insight into the physical relationships characterizing regional climate, and offers only an empirical basis for improvement. Nevertheless, statistically downscaled data from GCMs have proven useful in conjunction with local hydrological models for the estimation of streamflow and water resources in mountainous regions (Hostetler and Giorgi 1993; Leavesley 1994; Xu 1999; Gershunov et al. 2000; Miller 2001), and could be used with the results from high-resolution RCMs.

3.2 The PIER Focus

Impacts from climate change will affect California's ecosystems, infrastructure, and economy. Modeling these changes helps State decision makers and planners envision and implement the activities that will b e necessary to protect these systems effectively. However, California's unique palette of microclimates, ecosystems, and land uses requires regional modeling that challenges existing modeling technologies. To be able to model regional climate in California with a better degree of certainty, researchers must identify and improve upon regional models and modeling techniques, and develop a more comprehensive data set for the State.

Part of the mission of PIER is to conduct and fund research in the public interest that would otherwise not occur. Research to develop regional climate modeling that focuses on California applications is one such effort. The results of this research would also extend to other state agencies (e.g., California Air Resources Board), which could use these tools and data for their own public benefit projects. PIEREA aims to address this topic through its

[2] The variations of the variables such as temperature, pressure, wind, and moisture around the edges of a selected region.

[3] Prescribed relationships between the large-scale structure and behavior, as portrayed in a model, and that on smaller, unresolved scales.

own targeted research and to attract collaborators that will share data and work with PIEREA.

Other PIEREA roadmap chapters address other aspects of the effect of climate change on California resources and systems. Whenever possible, PIEREA will coordinate these programs and seek outside collaborators to leverage funding and avoid overlapping research.

4. Current Research and Research Needs

In spite of the high level of current activity in regional climate modeling, there are a number of issues of particular relevance to California that have not been adequately examined. These mainly concern the intercomparison of models, the application of statistical downscaling, and the observational database. The research areas in need of attention in modeling regional climate change for California are therefore identified as:

1. Regional Model Intercomparison
2. Statistical Downscaling for Hydrologic Applications
3. Observational Database Development

It is important to note that researchers intercomparing regional models must have access to extensive computing resources if they are to adequately model California's regional climates.

The following discussion outlines the status of current work in these areas and identifies the needed research in more detail.

4.1 Regional Model Intercomparison

Although many regional models have been used to simulate the climate over selected regions of the United States and elsewhere (as recently summarized by Leung 2002), there has been little attempt to evaluate and intercompare the models at the needed resolution. Each investigation has used different model formulations at horizontal resolutions of about 50–100km in different regions over different time periods. As pointed out earlier, this resolution is insufficient to adequately resolve important features of California's topography, and the lack of standardized experimental conditions makes it difficult to identify characteristic model errors. A common nested model domain[4] needs to be identified and a regional modeling protocol developed.

The Program to Intercompare Regional Climate Simulations (PIRCS) at Iowa State University has examined the performance of a variety of RCMs in the simulation of selected drought and flood events in the central United States (Takle et al. 1999), but has not undertaken an intercomparison of interest to California. In Europe, regional model

[4] A selected area in a global or large-scale model within which a higher-resolution model is imbedded.

intercomparison has been carried out for selected areas (Jacob 2001), and a comprehensive intercomparison for all of Europe has recently been launched under European Union sponsorship. This project (PRUDENCE) will include several European RCMs at high resolution run under several forcing scenarios for the European area (D. Jacob, personal comm.).

Recent research at the Lawrence Livermore National Laboratory (LLNL) has focused on the simulation of climate and climate change at the highest resolution (50 km) yet achieved with a global model. This research (supported by both the U.S. Department of Energy (DOE) and LLNL) provides an unprecedented opportunity to validate conventional RCMs at comparable resolution, while serving as the basis for regional modeling at even higher resolutions. The LLNL Program for Climate Model Diagnosis and Intercomparison (PCMDI) has extensive experience in the comparative evaluation of GCM performance, and has developed versatile software for data retrieval, diagnosis, and display.

Research Needs

There is an urgent need for the systematic comparative testing, analysis, intercomparison and validation of RCMs for California at resolutions of about 20 km. The RCM intercomparison should include several driving GCMs and several RCMs at the highest possible resolution. Comparisons should result in an ensemble of regional climate change projections that would permit researchers to determine definitively the models' characteristic errors and to prepare robust estimates of the statistical confidence with which regional California climate changes can be simulated.

4.2 Statistical Downscaling for Hydrologic Applications

The statistical downscaling of GCM results needs to keep pace with resolution increases in regional models, with which they should be systematically compared. The economy and flexibility of statistical downscaling need to be exploited in the development of improved local hydrologic models (Wilby et al. 2000; Hay et al. 2000; Wilby et al. 1998).

At the Scripps Institution of Oceanography (SIO), research supported by the National Oceanic and Atmospheric Administration (NOAA), DOE and the U.S. Geological Survey (USGS) is focused on the sensitivity of the Sierra snowpack and streamflow to climate change, using statistical techniques to downscale the output from GCMs (Wilby and Dettinger 2000). Related research addresses the effects of climate change on selected watersheds and the Sacramento-San Joaquin Delta (Knowles and Cayan 2001) and of the El Niño–Southern Oscillation (ENSO) on the statistics of temperature and precipitation extremes (Gershunov et al. 2000). Other Scripps studies supported by NOAA are using RCMs to generate high-resolution seasonal forecasts over California, from which researchers can derive climatological statistics useful in water management (J. Roads, personal comm.).

At the National Center for Atmospheric Research (NCAR), Tom Wigley is continuing research on the statistical regression of large-scale variables onto regional or local scales

(Hakkarinen and Smith 2001), while others at NCAR are preparing guidelines for the use of downscaled climate information in impact studies, including hydrology (Mearns and Wilby 2002). At the Lawrence Berkeley National Laboratory (LBNL), researchers have developed statistical downscaling regression models to estimate the regional hydrologic impacts of precipitation (Kyrakidis et al. 2000).

Research Needs

Important research gaps in the statistical downscaling of regional climate for hydrologic applications include: (1) the need for an evaluation of the statistical methods in comparison to regional climate modeling using as nearly the same boundary conditions as possible, (2) the need for further research on the effects of the possible variation of the statistical relationships over time, and (3) more adequate treatment of the water and energy budgets in regions with non-uniform surface characteristics.

4.3 Observational Database

Availability of observational data is fundamental to the success of regional climate models, not only so that they can deliver meaningful results, but also so that researchers can evaluate their performance confidently. Although selected California data are available at a number of institutions, a comprehensive and easily accessible regional California climate database has not been constructed.

Both the National Center for Atmospheric Research (NCAR) and the Western Regional Climate Center at the Desert Research Institute (University of Nevada) routinely collect climatological data for California, and the latter institution in particular has extensive supplemental data from local California sources. The National Center for Atmospheric Research is developing, with partial support from the Electric Power Research Institute (EPRI), a data access system for selected GCM data; it has not, however, been applied to regional data and is less flexible than the data access software developed at LLNL. Although not explicitly concerned with regional climate data, the California Air Resources Board (ARB) has collected regional meteorological and air pollution data during a number of test periods. These data may be useful additions to the proposed regional climate database, as might the data holdings of other state and private organizations, including the California Data Exchange Center (CDEC). A new regional reanalysis for the entire United States is being planned by NOAA's National Centers for Environmental Prediction (Mesinger et al. 2002), and that project should be a valuable guide for a similar effort addressing California.

Research Needs

All available regional California climate data need to be assembled into a comprehensive quality-controlled database, and a software system with flexible and robust input-output software needs to be developed for efficient documentation, access, and display of these data. Particularly needed for model validation are data on regional atmospheric, hydrologic, and land-surface processes at high resolution; information on the occurrence of extreme and unusual events; and new measurements of precipitation, snowpack, and soil moisture in the higher elevations of the Sierra. Such observations would be of value to water management practices in the state even in the absence of climate change. Although progress is being made in the assembly of regional data for RCM validation elsewhere (Widmann and Bretherton 2000; New et al. 2000), no such effort has been initiated for California.

5. Goals

The importance of reducing the uncertainty surrounding possible climate changes in California stems from the vulnerability of the State's water supply and almost all aspects of its economy. Faced with such a challenge, it is necessary to focus on the modeling issues that are the most relevant to California. This can best be done by creating a coordinated program with a clearly articulated goal, strategy, and implementation plan.

The goal of the Regional Climate Modeling portion of the PIER Climate Change Research Plan is to help California develop a comprehensive understanding of likely regional climate changes that will affect the State's hydrologic and agricultural infrastructure and natural ecosystems.

To reach this goal, efforts must support research that is most likely to improve regional climate modeling for California, as distinct from that which may be most useful in a general or global sense. The relevant projects are thus identified as: (1) high-resolution model intercomparison, (2) statistical downscaling for hydrologic applications, and (3) observational database development.

Section 5.1 outlines the anticipated objectives or milestones over the short-, mid-, and long-term[5] for the recommended research projects, together with the factors that are likely to be critical to the projects' success. All projects are seen as continuing over the short, mid and long terms.

The PIEREA program recognizes that much work is currently under way in these and related areas, and seeks to draw from, build upon, and broaden the focus of those efforts. Whenever possible, PIEREA will identify relevant existing efforts and will seek to form partnerships to leverage resources.

[5] S*hort-term* refers to a 1–3 year time frame; *mid-term* to 3–10 years; and *long-term* to 10–20 years. The activities specified in the roadmap are projected to begin sometime within the designated time frames, and the duration of actual projects may be less than the entire term specified.

5.1 Short-term Objectives

5.1.1 Regional Model Intercomparison

A. Design a model intercomparison protocol.

Activities needed: (1) Define a common domain for California RCMs. (2) Select atmospheric GCMs. (3) Determine a simulation length and resolution. (4) Identify and document participating RCMs.

B. Perform control simulations and analyze results.

Activities needed: (1) Run the selected GCMs. (2) Determine systematic errors of GCMs. (3) Repeat with selected imbedded RCMs at high resolutions per protocol. (4) Analyze systematic errors of RCMs driven by GCM control and reanalysis runs, including the mean and variability of selected critical variables over diurnal, seasonal, interannual, and decadal timescales, including extreme precipitation events.

Critical Factors for Success:
- Availability of computer time.
- Liaison with modeling community.
- Interface with impacts community.

5.1.2 Statistical Downscaling for Hydrologic Applications

A. Evaluate downscaling methods.

Activities needed: (1) Determine relative accuracy of alternative downscaling techniques. (2) Compare performance with comparable regional models.

B. Analyze errors of hydrologic applications.

Activities needed: (1) Evaluate sensitivity of selected hydrologic variables to downscaling errors. (2) Determine hydrologic variables' sensitivity to resolution.

Critical Factor for Success:
- Availability of observational data.

5.1.3 Observational Database

A. Develop a California climate database.

Activities needed: (1) Collect all available local and regional data. (2) Document data and place into the database.

B. Develop a data access system.

Activities needed: (1) Develop software for data storage, access, diagnosis, and display. (2) Distribute data to the research and impacts communities.

Critical Factor for Success:

- Cooperation of public and private data holders.

Table 1. Short-term Budget

Project Objective	Projected Cost ($000 per year)*
5.1.1.A Design a model intercomparison protocol	800 total for A & B
5.1.1.B Perform control simulations and analyze results	
5.1.2.A Evaluate downscaling methods	400 total for A & B
5.1.2.B Analyze errors of hydrologic applications	
5.1.3.A Develop a California climate database	600 total for A & B
5.1.3.B Develop a data access system	
Total Short-term Cost per Year	**1,800**

* There is a high probability that approximately equal funding will be available for each project from other sources. The figure given is the California Energy Commission's projected expenditure over the short-term period.

5.2 Mid-term Objectives

5.2.1 Regional Model Intercomparison

A. **Perform climate change simulations.**

Activities needed: (1) Run ensemble of high-resolution (50-km) GCM greenhouse scenarios. (2) Make parallel runs with selected imbedded RCMs at high resolutions (50 km and 20 km) per protocol.

B. **Analyze model results.**

Activities needed: (1) Determine ensemble characteristics of RCMs' simulated climate changes and changes in variability for wide range of variables, processes, and timescales, including coastal climate and extreme precipitation events. (2) Estimate statistical confidence of results. (3) Prepare probabilistic estimates of climate changes (including upper and lower bounds).

C. **Include new/improved models in intercomparison.**

Activities needed: (1) Perform simulations per protocol. (2) Analyze model results. (3) Compare with statistically downscaled results.

Critical factors for success:
- Availability of computer time.
- Liaison with modeling community.

5.2.2 Statistical Downscaling for Hydrologic Applications

A. **Develop improved downscaling techniques.**

Activities needed: (1) Incorporate physical considerations into downscaling. (2) Incorporate supplemental local data. (3) Examine statistical stability over longer time periods.

B. **Improve coupled hydrologic models.**

Activities needed: (1) Evaluate needed regional detail in parameterization. (2) Determine response sensitivity as a function of scale. (3) Improve models' energy and water budgets.

Critical factor for success:
- Availability of observational data.

5.2.3 Observational Database

A. **Incorporate new data.**

Activities needed: (1) Identify and support acquisition of new hydrologic observations in higher elevations of the Sierra. (2) Identify and support new surface observations in other regions of state. (3) Recover undigitized and remotely sensed data. (4) Distribute downscaled data to impact assessment groups.

B. **Perform reanalysis for California.**

Activities needed: (1) Use the selected RCM to perform high-resolution long-term reanalysis with all available data. (2) Add reanalysis data to database.

Critical factors for success:
- Support of other public agencies for new observations.
- Availability of computer time.

5.3 Long-term Objectives

5.3.1 Regional Model Intercomparison

A. **Expand intercomparison.**

Activities needed: *(1) Incorporate new/improved models, including those with coupled chemical, hydrologic, and biological processes. (2) Perform expanded ensemble of control and climate change runs per protocol. (3) Refine simulations' error statistics. (4) Refine probabilistic estimates of climate changes.*

B. **Develop innovative solution methods.**

Activities needed: *(1) Design and incorporate interactive regional resolution. (2) Develop and apply non-hydrostatic models to resolve changes on scales in the 1–10 km range.*

Critical factors for success:
- Availability of computer time.
- Liaison with modeling community.

5.3.2 Statistical Downscaling for Hydrologic Applications

A. **Develop hybrid downscaling approach.**

Activities needed: (1) Combine modeling and statistical downscaling approaches. (2) Determine the model's systematic errors.

B. **Systematic model use in hydrologic applications.**

Activities needed: (1) Examine the stability of parameter representation. (2) Document model applicability in different regions.

Critical factor for success:
- Availability of observational data.

5.3.3 Observational Database

A. **Continue database development.**

Activities needed: (1) Continue support of new data acquisition. (2) Add selected satellite, marine, and ecological data. (3) Improve data software system.

B. **Promote database use.**

Activities needed: (1) Use as data-of-choice for model validation. (2) Publicize database to public and private sectors.

Critical factor for success:
- Cooperation and support of other agencies.

5.4 Implementation

The key to the success of the proposed California climate change modeling initiative is to implement it as a *program,* with defined targets and priorities, and in which each element has a clear relationship to the others. Such a program would require the California Energy Commission to hire a research manager whose duties should include scientific overview of the program's projects, preparation of program reports for the Commission and others, coordination with appropriate national and international efforts, and the maintenance of effective outreach and public relations. Ideally, this manager should be experienced in climate modeling and research so that he/she can ensure that the results are used effectively.

Coordination among the various research projects requires that each project be aware of the work of the other projects being supported, especially in those cases where the success of one project is dependent on the results of another. A participation protocol should be developed under which each project would agree to share its findings (prior to their publication in the scientific literature), to contribute its results and/or data to a common database, and to employ common standards and procedures whenever possible. Coordination would also be increased by regular meetings of the program's investigators, at which the projects' results would be reported and future programmatic plans discussed.

Rather than supporting a large number of separate research tasks (in the manner, say, of the National Science Foundation, or NSF), it is recommended that the program instead be organized around a small number of basic collaborative projects that focus on issues of critical importance to California and to which unique local capabilities can be brought to bear. In this way, the desired level of cooperation among the groups participating in each project can be built into the program from the beginning. Among the three recommended projects, regional model intercomparison is seen as the core of the program, although it is recommended that an overall program balance be maintained. Support of research in statistical downscaling for hydrologic applications is of particular importance for California, and the assembly of a comprehensive observational database is of value across the program.

In view of the unique and widely recognized experience of the potential California participants, it is recommended that competitive bidding be used to select the groups best qualified to carry out the recommended research. The availability of co-funding from other sources should be an important consideration.

6. Leveraging R&D Investments

In order to use the funds available for the research recommended in this roadmap most effectively, it is important that they be leveraged whenever possible and appropriate against the support that is (or may be) available from other sources. In particular, leveraged support should be sought with relevant ongoing projects at the University of California campuses and laboratories, supported by the DOE, NSF, the National Aeronautics and Space Administration (NASA), and NOAA.

6.1 Methods of Leveraging

- Much of the work identified in this roadmap would be collaborative with other entities; PIEREA would either co-fund projects by other entities, or use outside funds to support PIEREA efforts.

6.2 Opportunities

Co-sponsorship opportunities are likely under the following scenarios:

- The DOE currently supports research on statistical downscaling for the western United States at the Scripps Institution of Oceanography under the pilot Accelerated Climate Prediction Initiative (ACPI) project, and supports limited research on regional modeling at Pacific Northwest National Laboratory (PNNL) and at the Universities of Maryland and Quebec under the Climate Change Prediction Program (CCPP). The ACPI proposed the establishment of several centers for regional climate prediction and application, but the initiative was unfortunately not implemented. In the spirit of ACPI, efforts should be made to secure support from DOE's Office of Biological and Environmental Research for the PIER regional climate modeling program, in which California could serve as a useful test bed for the development of a subsequent national effort.

- The DOE and LLNL currently support research on high-resolution climate modeling in the Laboratory's Energy and Environment Directorate. Plans are being developed for the extension of this work.

- The NOAA currently supports research at Scripps on the use of regional models for seasonal forecasting in California, and supports research on their use for regional climate simulation at LBNL (in cooperation with NASA). The NSF supports considerable research that is relevant to regional climate modeling at universities and at NCAR.

- The U.S. Global Change Research Program (USGCRP) coordinates a wide range of relevant climate modeling research supported by the NSF, NOAA, DOE and NASA, and endorsement of the proposed program by the USGCRP would be useful.

7. Areas Not Addressed by This Roadmap

There are several areas that are relevant to the modeling of regional California climate and climate change that are not recommended for PIER support at this time. These are:

- The development of new global or regional models. There is a sufficient number of both kinds of models now available, and their improvement is an important ongoing objective principally supported by the NSF and other federal agencies. As improved models are developed, however, it is important that PIER follow their status so that their suitability for inclusion in the PIER model intercomparison can be evaluated.
- The development or use of impact assessment models. Models of the impact of climate change on specific activities, such as crop production or tourism, should be funded primarily by the appropriate state agencies or by the private sector.
- The use of regional models for weather forecasting. Regional models are commonly used in numerical weather prediction and are increasingly being applied in seasonal forecasting. This work is amply supported by NOAA.
- The use of regional models for the simulation of paleoclimate. Although the reconstruction of past climates provides a unique view of climate changes, the data are sparse, and not necessarily representative of future changes in California climate.

It is recommended, however, that the program maintain an awareness of developments in these areas as a source of supplementary information and possible future cooperative projects.

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Appendix A
Current Status of Programs

This section outlines those efforts in California, the United States, and abroad that most closely address the regional modeling of climate change.

Current Status: California

California Air Resources Board (ARB)

- Although not explicitly concerned with regional climate modeling, ARB has supported the development of the MM5 regional model for use with high-resolution photochemical models for the short-term prediction of air quality, and has collected meteorological and air pollution data during a number of regional test periods. This experience and these data may be useful in the proposed regional climate modeling program.

Lawrence Berkeley National Laboratory (LBNL)

- Use of regional climate models to drive high-resolution hydrologic models for selected Sierra watersheds (Norm Miller). This research is supported by NOAA and NASA. The regional model is itself forced by the control and increased CO_2 scenarios from GCMs, as well as by global reanalyses (Miller and Kim 2000; Kim[6] 2001).

Lawrence Livermore National Laboratory (LLNL)

- Research supported by the Laboratory in its Energy and Environment Directorate has enabled the commencement of a multi-year integration of the NCAR GCM with a global horizontal resolution comparable to that currently used in many RCMs (i.e., ~50 km). This work will permit direct examination of the accuracy of an imbedded RCM at this resolution (P. Duffy, personal comm.). Other relevant research at LLNL focuses on the analysis and intercomparison of the systematic errors of GCMs and the development of diagnostic software in the Program for Climate Model Diagnosis and Intercomparison.

Scripps Institution of Oceanography (SIO), University of California at San Diego

- Use of statistical downscaling techniques to apply GCM-simulated climate changes to hydrologic models for the western United States, including snowfall and streamflow in the Sierra (Dan Cayan). This research is part of the DOE ACPI pilot project, with related support from NOAA and USGS. Scripps is also conducting research with an RCM to study the effects of El Niño on California streamflow.

National Centers for Environmental Prediction, NOAA, Washington, D.C.

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[6] Jinwon Kim recently moved to UCLA, where he will use a regional climate system model to study the impact of climate change on hydrology and agriculture (J. Kim, personal comm.).

- Planning for a U.S.-wide, regional-scale reanalysis, using the operational ETA model (Fedor Mesinger).

University of California at Davis (UCD), Department of Land, Air, and Water Resources

- Use of regional climate models for study of vegetative surface fluxes over the western United States (Bryan Weare).

University of California at Los Angeles (UCLA), Department of Atmospheric Sciences

- Use of regional climate models to simulate climate change in California, with emphasis on Sierra precipitation (Jinwon Kim).

University of California at Santa Cruz (UCSC), Department of Earth Sciences

- Use of a regional climate model for simulation of climate change in California, in collaboration with LLNL (Lisa Sloan).

Current Status: Regional and National

Desert Research Institute (DRI) of the University of Nevada, Reno, Nevada

- Reconstruction of past precipitation fluctuations in Central Valley from blue oak tree-ring widths, and maintenance of regional climatological records (Kelly Redmond).

Electric Power Research Institute (EPRI), Palo Alto, California

- Cooperation with ACACIA project at NCAR and with PIRCS project at Iowa State University (Chuck Hakkarinen).

Iowa State University (ISU), Department of Atmospheric Sciences, Ames, Iowa

- ISU is evaluating the performance of a variety of regional climate model simulations as part of the Project to Intercompare Regional Climate Simulations (PIRCS), with emphasis on hydrology (Bill Gutowski, Gene Takle, Ray Arritt). Examinations are focusing on selected drought and flood events in the central United States (Takle et al. 1999), and on the uncertainties in regional downscaling (Pan et al. 2001). This work has support from both EPRI and NOAA.

National Center for Atmospheric Research (NCAR), Environmental and Societal Impacts Group, Boulder, Colorado

- The National Center for Atmospheric Research is continuing research on the statistical regression of large-scale variables onto regional or local scales, and is developing a data access system with partial support from EPRI (Hakkarinen and Smith 2001). Linda Mearns and Tom Wigley of NCAR are preparing guidelines for the use of downscaled climate information (Mearns and Wilby 2002), and participating in an NCAR impact assessment initiative (L. Mearns, personal comm.).

Pacific Northwest National Laboratory (PNNL), Richland, Washington

- Use of regional climate models for the Pacific Northwest, including downscaling to hydrologic variables (Ruby Leung), as part of the ACPI pilot project supported by DOE in cooperation with Scripps.

Current Status: International

European Union (EU)

- The European Union is continuing to sponsor the development, application, and intercomparison of regional climate models over selected regions in Europe (Giorgi and Francisco 2000 a, b; Jacob et al. 2001; Hagemann et al. 2001; Christensen et al. 2001). The EU has also recently launched a new project (PRUDENCE) in which the performance of several RCMs driven by the Hadley Centre GCM will be intercompared for a 30-year period over Western Europe.

Hadley Centre for Climate Prediction and Research, United Kingdom Meteorological Office (UKMO), Bracknell, UK

- High-resolution models are being used to examine the effects of the RCM's domain on the quality of the simulated regional climate, driven by the centre's operational GCM (R. Jones, personal comm.)

Max-Planck Institute for Meteorology (MPI), Hamburg, Germany

- Research is under way on the sensitivity of simulated regional climate to the parameterization of surface process with resolutions of 1/2 and 1/6 degree (D. Jacob, personal comm.).

University of Quebec, Montreal, Canada

- At the University of Quebec in Montreal, research is under way on the effects of an RCM's resolution and lateral boundary conditions in an experiment similar to that underway at LLNL (Denis et al. 2002a, b), although focused on eastern North America. A new Canadian Regional Climate Modelling Network has recently been established to pursue a broad range of relevant research over the next several years (R. Laprise, personal comm.).